working with Keith on

Gravitino Dark Matter

models

Vassilis C. Spanos
UoA

Olivefest 2017, Mnpls 19/5/2017

Outline

- Keith's early Gravitino days
- Now: why still SUSY, Supersymmetric DM scenarios
- Direct, indirect searches of DM
- Gravitino Dark Matter
- Gravitino thermal production and reheating temperature
- Recap

Nuclear Physics B238 (1984) 453–476

SUPERSYMMETRIC RELICS FROM THE BIG BANG*

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Received 16 September 1983
(Revised 15 December 1983)

We consider the cosmological constraints on supersymmetric theories with a new, stable particle. Circumstantial evidence points to a neutral gauge/Higgs fermion as the best candidate for this particle, and we derive bounds on the parameters in the lagrangian which govern its mass and couplings. One favored possibility is that the lightest neutral supersymmetric particle is predominantly a photino $\tilde{\gamma}$ with mass above $\frac{1}{2}$ GeV, while another is that the lightest neutral supersymmetric particle is a Higgs fermion with mass above 5 GeV or less than O(100) eV. We also point out that a gravitino mass of 10 to 100 GeV implies that the temperature after completion of an inflationary phase cannot be above 10^{14} GeV, and probably not above 3×10^{12} GeV. This imposes constraints on mechanisms for generating the baryon number of the universe.

Volume 145B, number 3,4 PHYSICS LETTERS 20 September 1984

COSMOLOGICAL GRAVITINO REGENERATION AND DECAY

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CERN, Geneva, Switzerland

Received 29 May 1984

We present a detailed study of gravitino production and decay subsequent to cosmological inflation. We calculate the cross sections for gravitino production in collisions of particles in the supersymmetric standard model, and use them to calculate the regenerated abundance of gravitinos as a function of the maximum reheating temperature T_{max}. An upper limit on the gravitino mass density during cosmological nucleosynthesis requires $T_{max} < 0.90 \times 10^{16}$ GeV and considerations of the entropy released when gravitinos decay require $T_{max} < 2.2 \times 10^{13}$ GeV, while more careful analyses of their decay products' disruptive effects on light nuclei and on the microwave background radiation suggest $T_{max} < 10^{9}-10^{10}$ GeV.

Nuclear Physics B255 (1985) 495–504

GRAVITINOS AS THE COLD DARK MATTER IN AN $\Omega = 1$ UNIVERSE

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Department of Physics, The University of California, Santa Barbara, CA 93106, USA

Received 26 October 1984

In attempts to simultaneously have galaxy formation with adiabatic fluctuations, dark galactic halos and a critical $\Omega = 1$, recent models have been proposed with a heavy (cold) species which decays and a lighter (hot or warm) one which is stable. Surprisingly enough, these models are very constraining. Independent of the particle physics model, the decay width of the heavy particle must be $O(10^{-40})$ GeV. Such a scale is only natural in theories involving gravity where one expects $\Gamma \sim M_H^3/M_P^2$, where M_H is the mass of the heavy particle and M_P is the Planck mass. In this paper, we suggest that the heavy particle might be the gravitino which is present in all supergravity theories. This model would then require that the gravitino decay products not include photons, indicating that the lightest supersymmetric particle (LSP) must be something other than the photino. An acceptable candidate for the LSP might be the axino, the supersymmetric partner of the axion.

VOLUME 55, NUMBER 21 PHYSICAL REVIEW LETTERS 18 NOVEMBER 1985

Diffuse Cosmic Gamma-Ray Background as a Probe of Cosmological Gravitino Regeneration and Decay

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and

Joseph Silk
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(Received 22 March 1985)

We predict the presence of a spectral feature in the isotropic cosmic gamma-ray background associated with gravitino decays at high red shifts. With a gravitino abundance that falls in the relatively narrow range expected for thermally regenerated gravitinos following an inflationary epoch in the very early universe, gravitinos of mass several gigaelectronvolts are found to yield an appreciable flux of 1–10-MeV diffuse gamma rays.

PACS numbers: 98.70.Vc, 11.30.Pb, 14.80.Pb, 95.30.Cq

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Physics Letters B 588 (2004) 7–16
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Gravitino dark matter in the CMSSM

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Editor: G.F. Giudice

Abstract

We consider the possibility that the gravitino might be the lightest supersymmetric particle (LSP) in the constrained minimal extension of the Standard Model (CMSSM). In this case, the next-to-lightest supersymmetric particle (NSP) would be unstable, with an abundance constrained by the concordance between the observed light-element abundances and those calculated on the basis of the baryon-to-entropy ratio determined using CMB data. We modify and extend previous CMSSM relic neutralino calculations to evaluate the NSP density, also in the case that the NSP is the lighter stau, and show that the constraint from late NSP decays is respected only in a limited region of the CMSSM parameter space. In this region, gravitinos might constitute the dark matter.

SUSY and Higgs mass

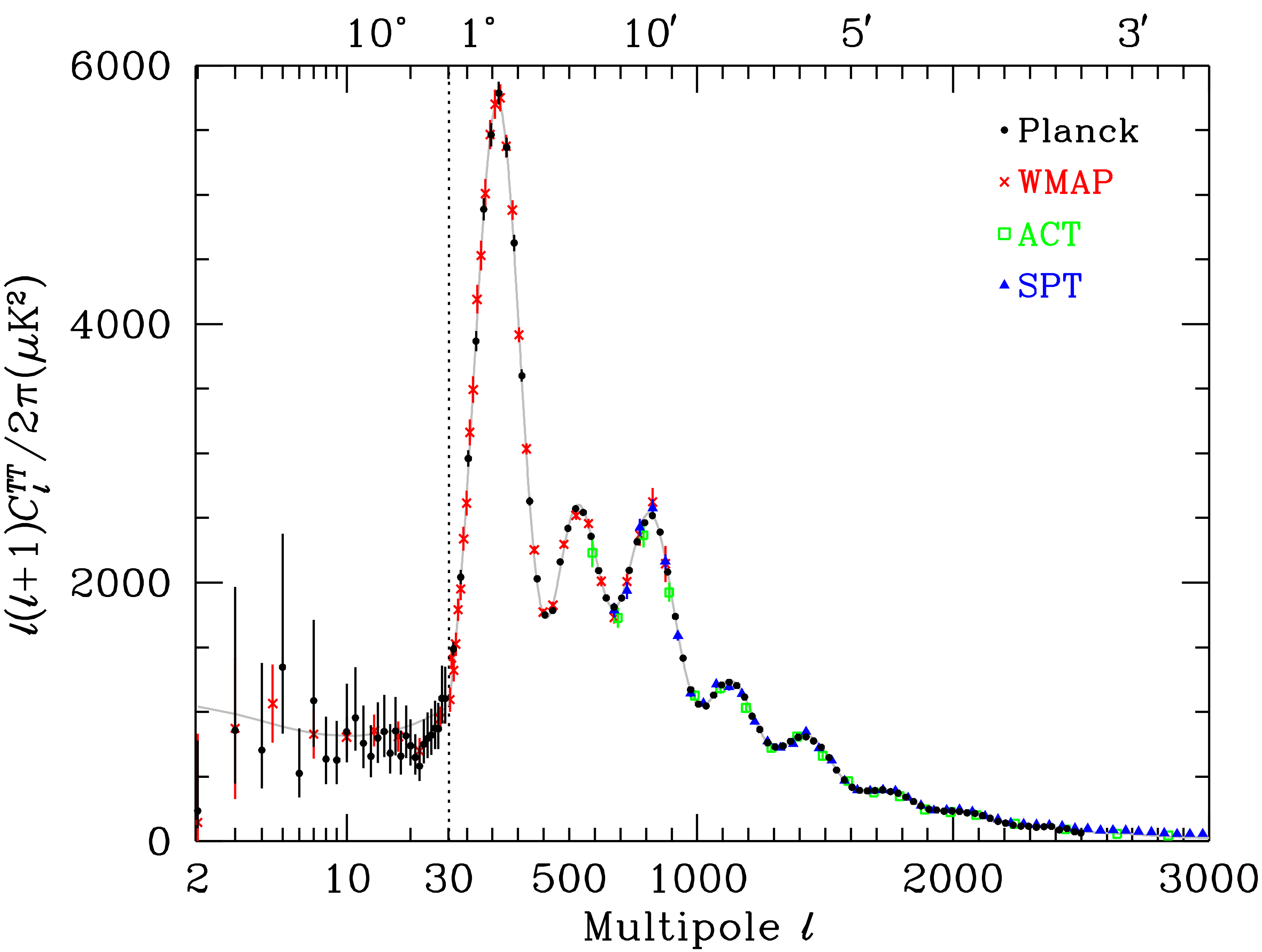
$$m_h = \sqrt{\frac{1}{2}[M_A^2 + M_Z^2 - \sqrt{(M_A^2 + M_Z^2)^2 - 4M_A^2 M_Z^2 \cos^2\beta}]} < M_Z$$

$$\tan\beta = \frac{v_2}{v_1}$$

$$\begin{aligned}\Delta m_h^2 \simeq & \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\log\left(\frac{m_{\tilde t}^2}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde t}^2} - \frac{X_t^4}{12 m_{\tilde t}^4}\right] \\ & - \frac{3}{48\pi^2}\frac{m_b^4}{v^2}\;\frac{t_\beta^4}{(1+\epsilon_b t_\beta)^4}\;\frac{\mu^4}{m_{\tilde b}^4} \\ & - \frac{1}{48\pi^2}\frac{m_\tau^4}{v^2}\;\frac{t_\beta^4}{(1+\epsilon_\ell t_\beta)^4}\;\frac{\mu^4}{m_{\tilde\tau}^4}\end{aligned}$$

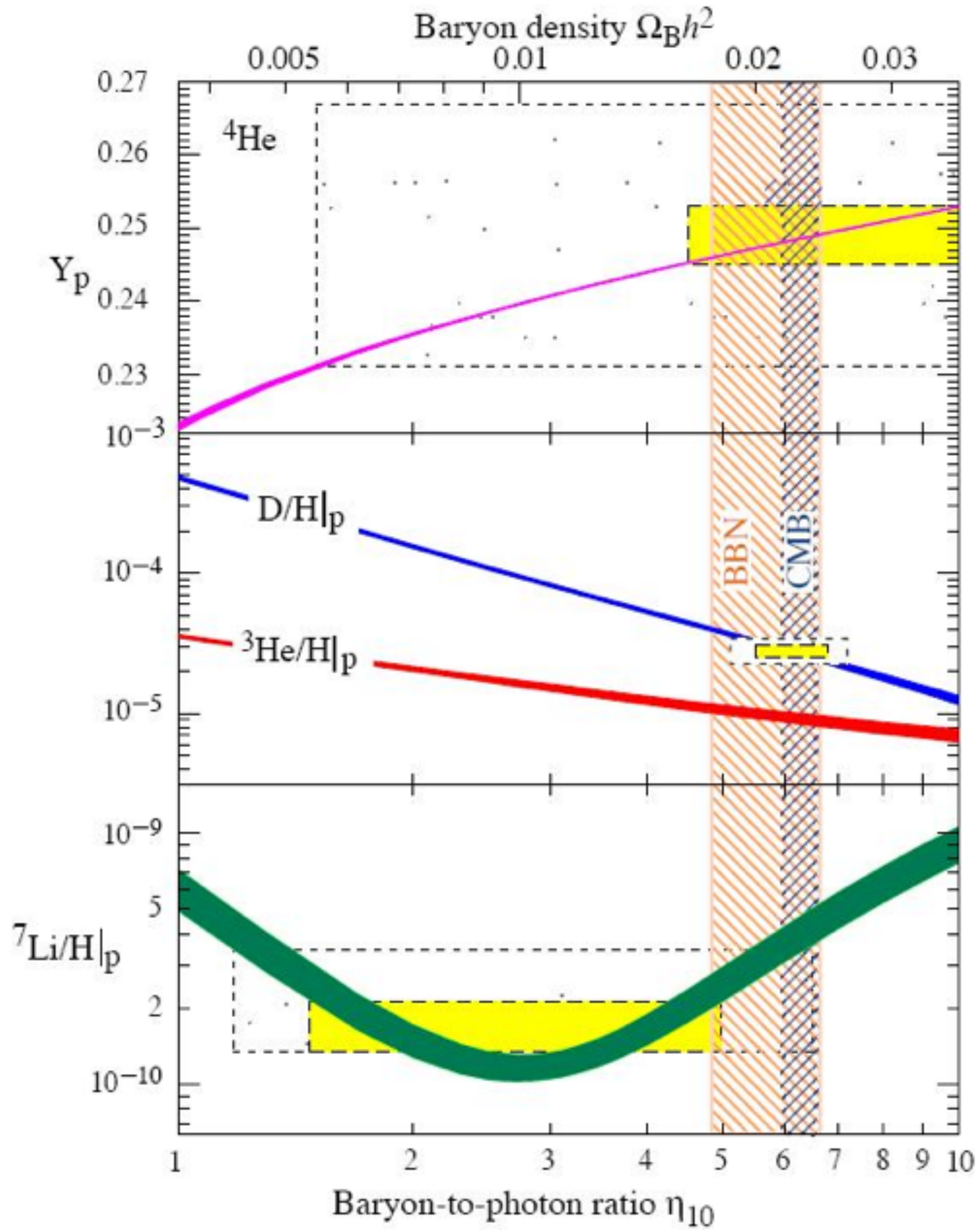
$$X_t = A_t + \mu/\tan\beta \approx A_t$$

DM/ Evidence



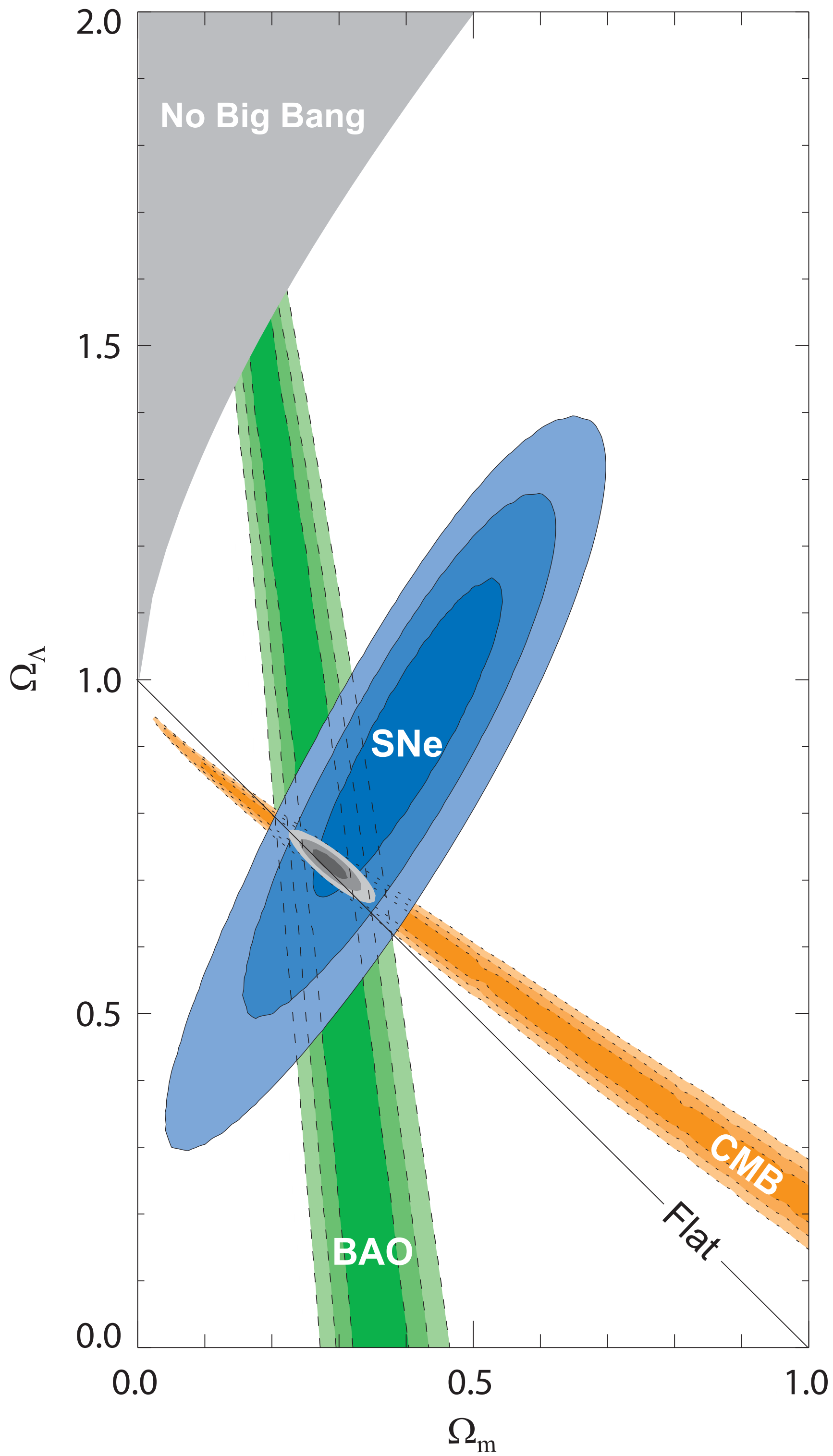
10°
1°
10′
5′
3′
6000
4000
2000
0
$\ell(\ell+1)C_\ell^{TT}/2\pi(\mu K^2)$
• Planck
× WMAP
□ ACT
▲ SPT
2
10
30
500
1000
2000
3000
Multipole ℓ

DM/ Evidence



Baryon density $\Omega_B h^2$
0.005
0.01
0.02
0.03
0.27
0.26
0.25
0.24
0.23
Y_p
^{4}He
10^{-3}
10^{-4}
10^{-5}
D/H|p
^{3}He/H|p
BBN
CMB
10^{-9}
5
2
10^{-10}
^{7}Li/H|p
1
2
3
4
5
6
7
8
9
10
Baryon-to-photon ratio η_{10}

DM/ Evidence



$$\Omega_{\rm tot} \sim 1.0$$

$$\Omega_{\rm M} = 0.315 \pm 0.016$$

$$\Omega_\Lambda = 0.685 \pm 0.017$$

$$\Omega_{\rm B} = 0.0499 \pm 0.0022$$

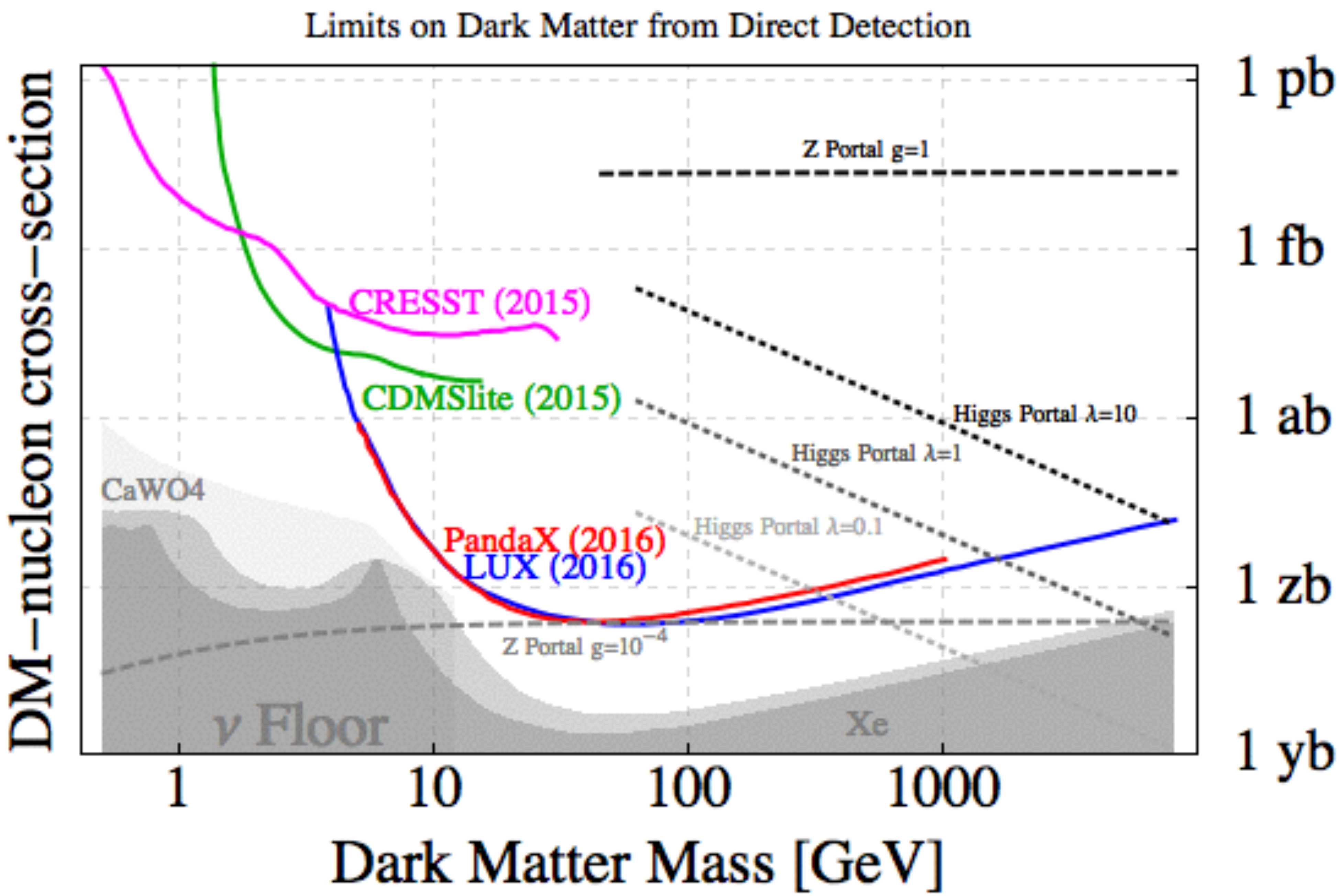
$$\Longrightarrow$$

$$\boldsymbol{\Omega_{\rm DM} = \Omega_{\rm M} - \Omega_{\rm B} = 0.265 \pm 0.011}$$

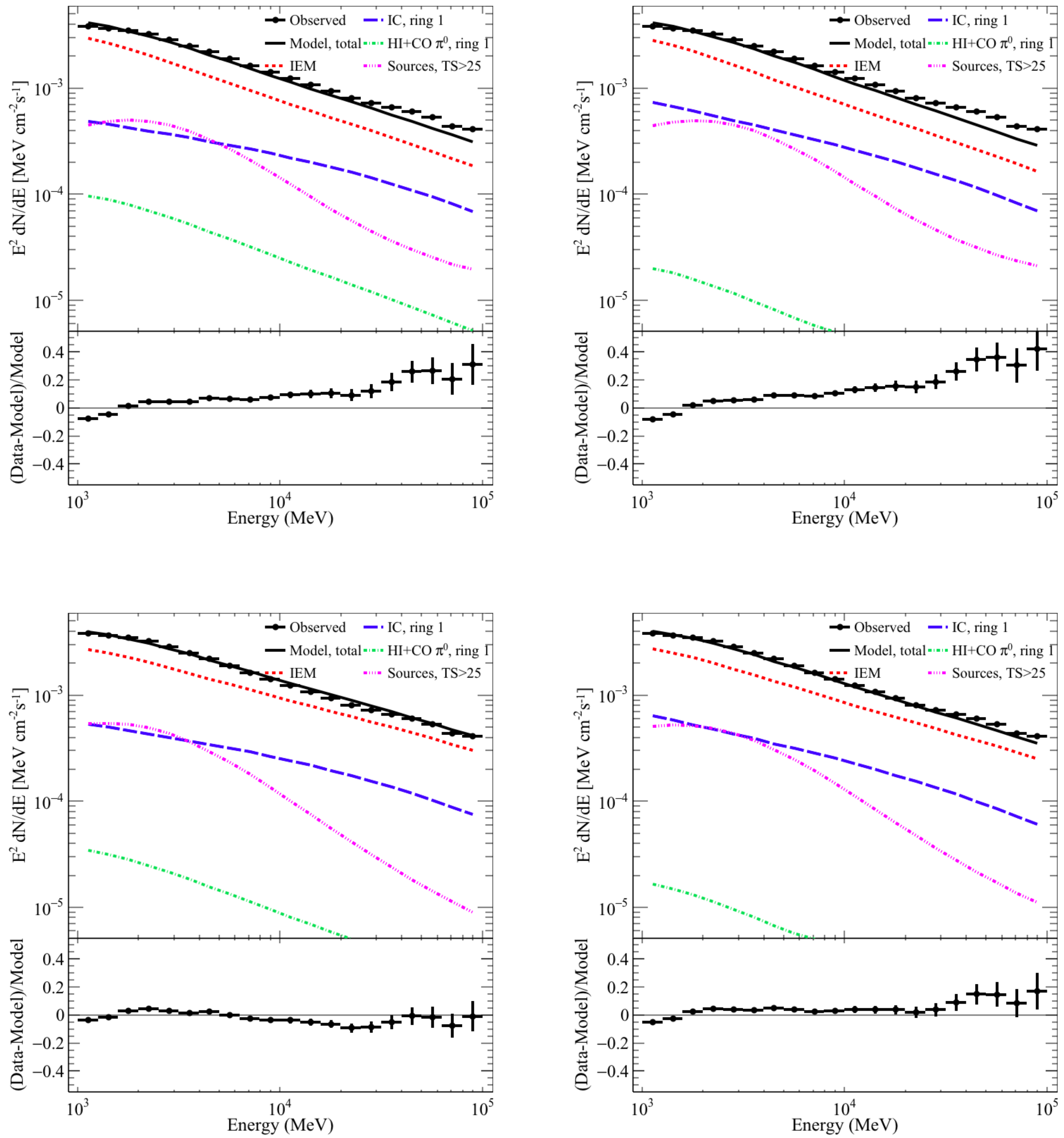
$$\Omega_\chi h^2 = 0.112 \pm 0.12$$

PDG-2016

DM/ Direct searches

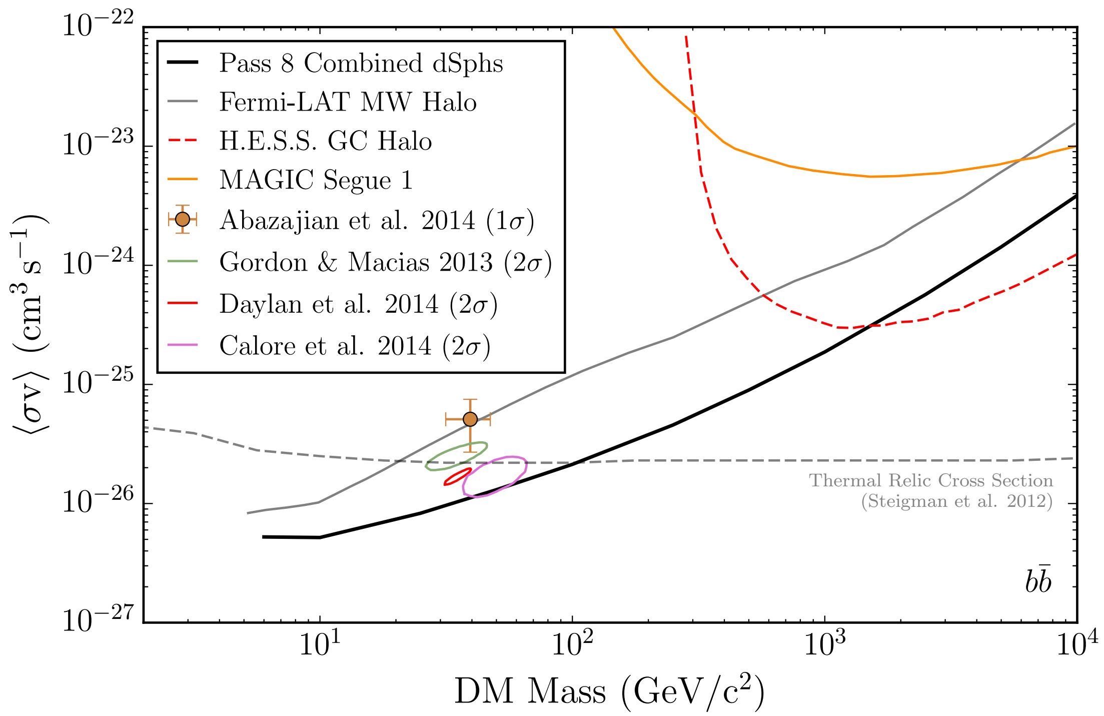


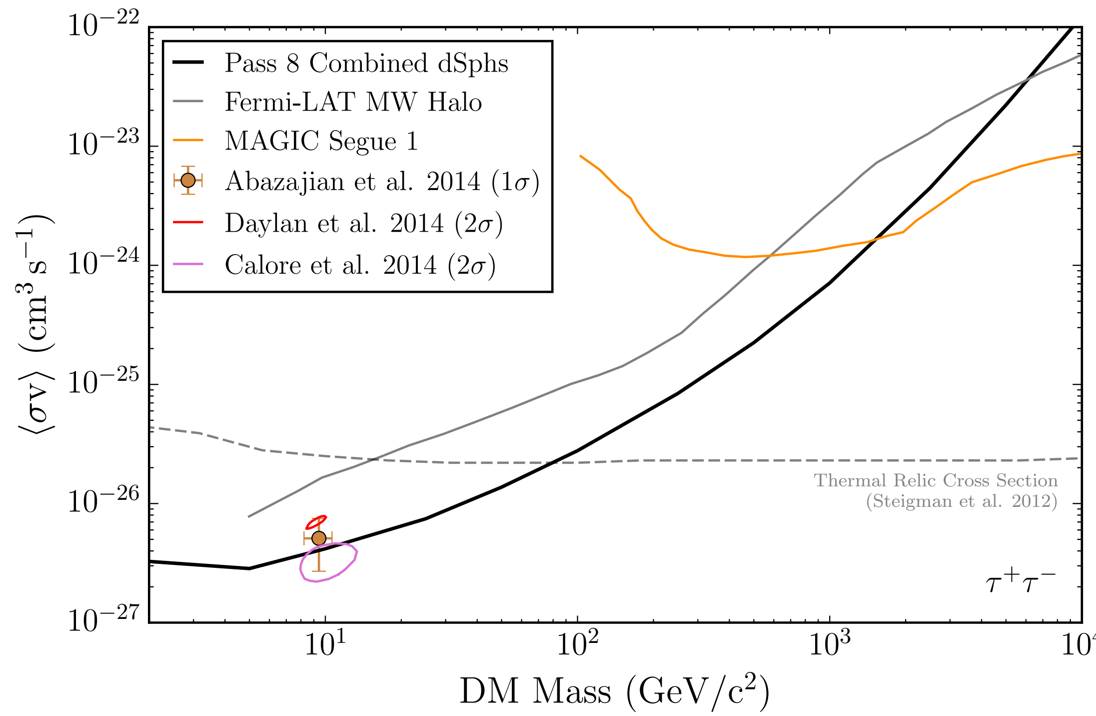
DM/ Indirect searches gammas GC



Fermi-LAT

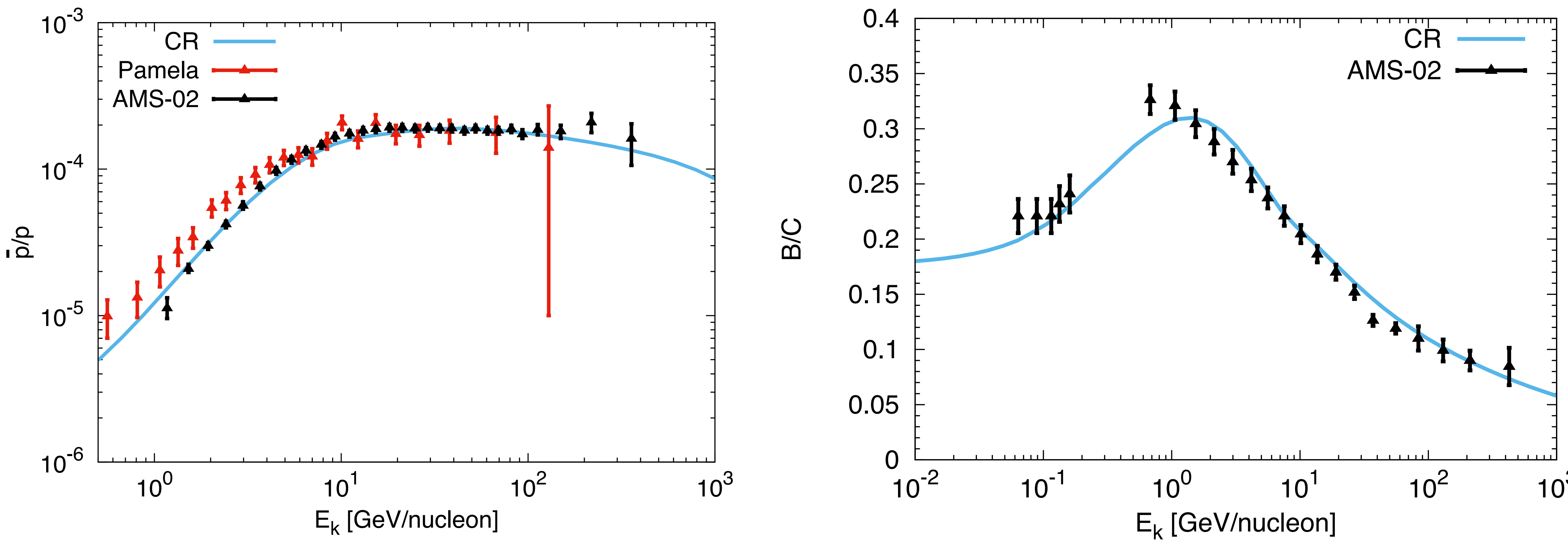
DM/ Indirect searches gammas dSph





Fermi-LAT

DM/ Indirect searches antiprotons



Ellis, Olive, VCS

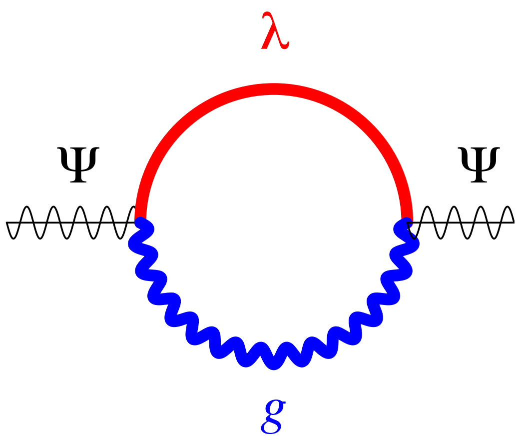
DM searches status

- Direct searches, up to date, have found nothing
- Indirect searches uncertainties: halo, direct x-section etc
- Neutralino models “currently not favoured” by LHC SUSY searches
- — Gravitino

Gravitino Dark Matter

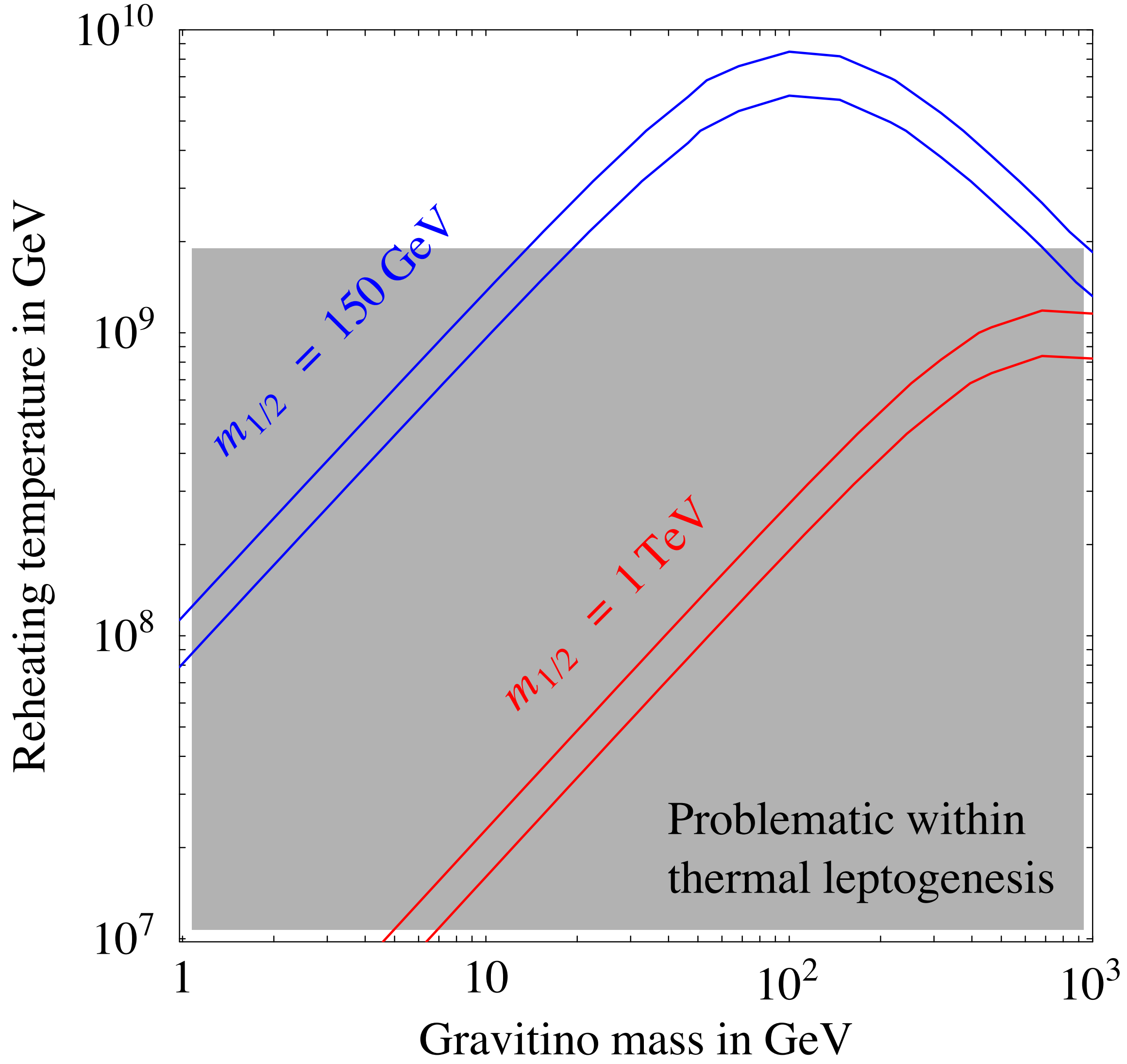
Gravitino thermal production

$$Y_{3/2}(T) \simeq 4.48 \times 10^{-11} \left(\frac{T_{\rm reh}}{10^{10}\,{\rm GeV}}\right) \times \left[\left(1 + 0.558\,\frac{m_{1/2}^2}{m_{3/2}^2}\right) - 0.011\left(1 + 3.062\,\frac{m_{1/2}^2}{m_{3/2}^2}\right)\ln\left(\frac{T_{\rm reh}}{10^{10}\,{\rm GeV}}\right)\right]$$



Important constraints from BBN data

Gravitino thermal abundance



Rychkov, Strumia

Big Bang Nucleosynthesis

Light Elements observed abundances:

- **^{4}He** observed in extragalactic HII regions:

  abundance by mass ~ **25%**

- **^{7}Li** observed in the atmosphere of dwarf halo stars:

  abundance by number ~ **10^{-10}**

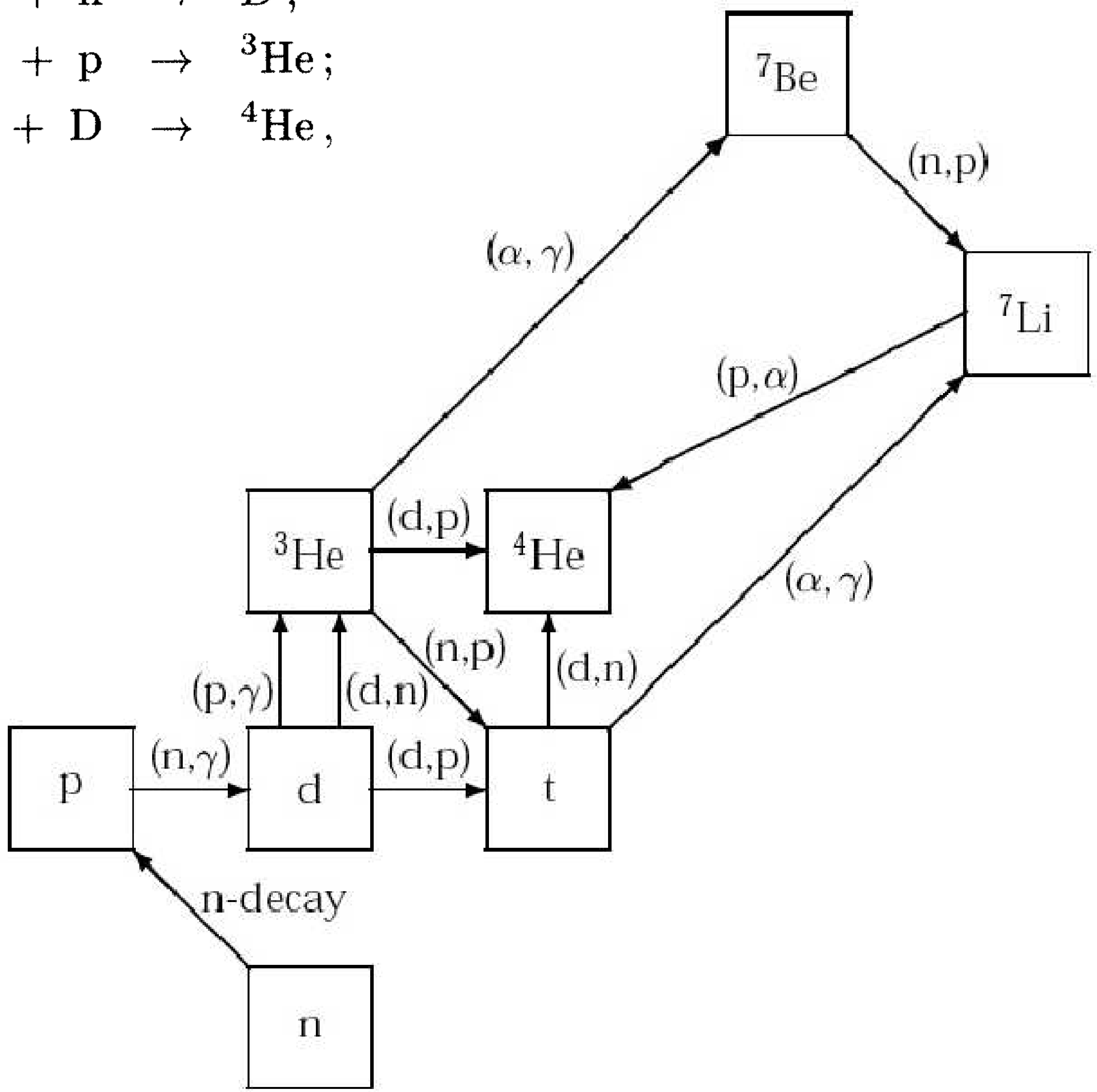
- **D** in quasars absorption systems (and locally):

  abundance by number ~ **3×10^{-5}**

- **^{3}He** observed in solar wind, meteorites, and in ISM:

  abundance by number ~ **10^{-5}**

$$\begin{array}{rcl} p + n & \rightarrow & D\,; \\ D + p & \rightarrow & {}^{3}\mathrm{He}\,; \\ D + D & \rightarrow & {}^{4}\mathrm{He}\,, \end{array}$$



Nucleosynthesis Delayed (Deuterium Bottleneck)

$$p + n \rightarrow \mathbf{D} + \gamma \qquad \Gamma_p \sim n_B \sigma$$

$$p + n \leftarrow \mathbf{D} + \gamma \qquad \Gamma_d \sim n_\gamma \sigma e^{-E_B/T}$$

Nucleosynthesis begins when $\Gamma_p \sim \Gamma_d$

$$\frac{n_\gamma}{n_B} e^{-E_B/T} \sim 1 \qquad \textbf{@ } T \sim 0.1 \textbf{ MeV}$$

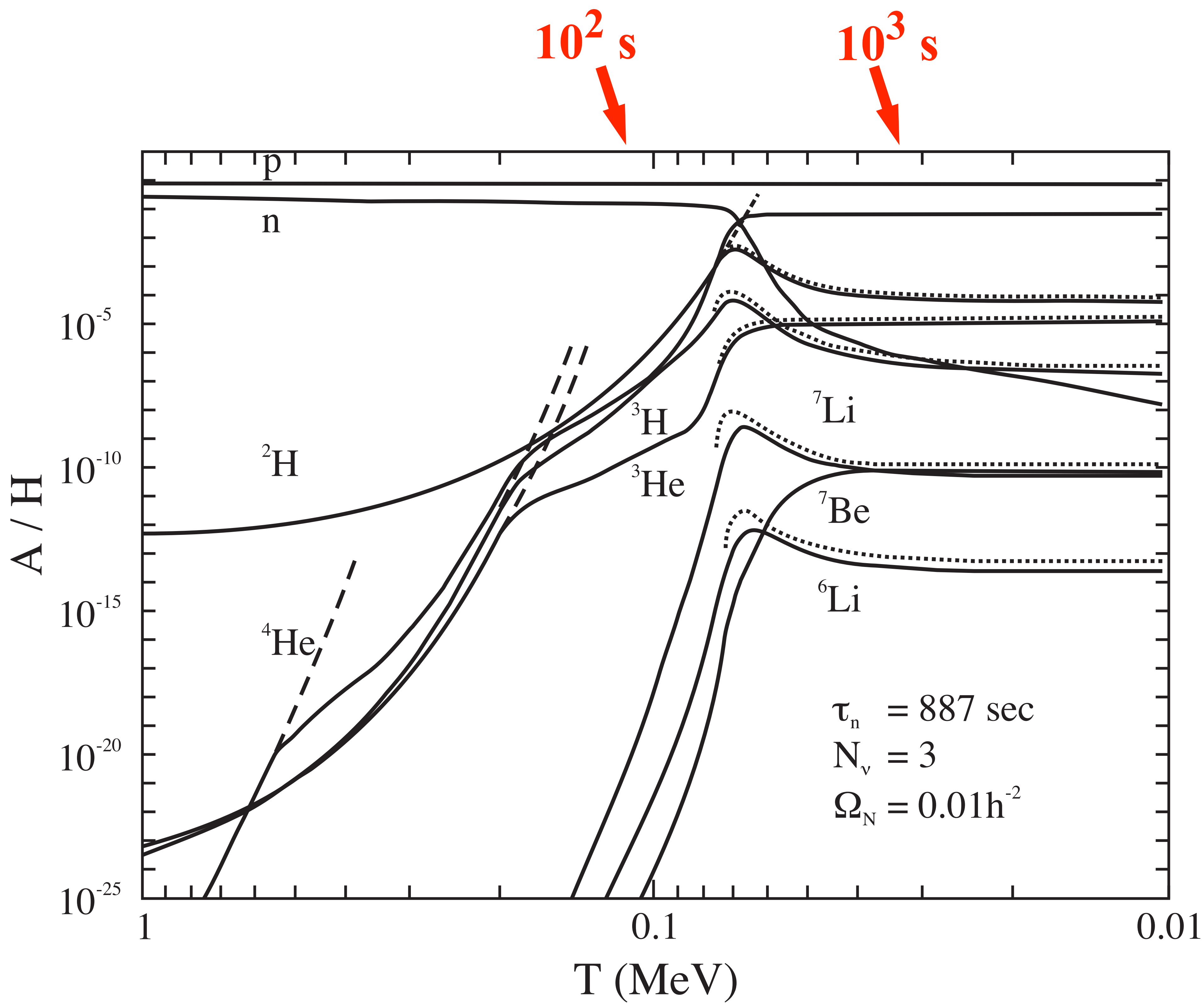
All neutrons $\rightarrow$ ^{4}**He**

$$Y_p = \frac{2(n/p)}{1 + (n/p)} \simeq 25\%$$

Remainder:

D, ^{3}**He** $\sim 10^{-5}$ **and** ^{7}**Li** $\sim 10^{-10}$ **by number**

Light elements production



Gravitino field representation

The four polarisation states of the gravitino field in the momentum space in terms of spin-1 and spin-1/2 components:

$$\begin{aligned}
\psi_\mu(\mathbf{k}, \tfrac{3}{2}) &= u(\mathbf{k}, \tfrac{1}{2})\, \epsilon_\mu(\mathbf{k}, 1)\,, \\
\psi_\mu(\mathbf{k}, \tfrac{1}{2}) &= \sqrt{\tfrac{1}{3}}\, u(\mathbf{k}, -\tfrac{1}{2})\, \epsilon_\mu(\mathbf{k}, 1) + \sqrt{\tfrac{2}{3}}\, u(\mathbf{k}, \tfrac{1}{2})\, \epsilon_\mu(\mathbf{k}, 0) \\
\psi_\mu(\mathbf{k}, -\tfrac{1}{2}) &= \sqrt{\tfrac{1}{3}}\, u(\mathbf{k}, \tfrac{1}{2})\, \epsilon_\mu(\mathbf{k}, -1) + \sqrt{\tfrac{2}{3}}\, u(\mathbf{k}, -\tfrac{1}{2})\, \epsilon_\mu(\mathbf{k}, 0) \\
\psi_\mu(\mathbf{k}, -\tfrac{3}{2}) &= u(\mathbf{k}, -\tfrac{1}{2})\, \epsilon_\mu(\mathbf{k}, -1)\,,
\end{aligned}$$

From the field equation for the spin-3/2 particle, the so called Rarita-Schwinger equation, we get three equations in momentum space, which we have to fulfill by the right choice of the spin-1 and spin-1/2 component representations

$$\begin{aligned}
\gamma^\mu \psi_\mu(\mathbf{k}, \lambda) &= 0 \\
k^\mu \psi_\mu(\mathbf{k}, \lambda) &= 0 \\
(\not{k} - m_{\widetilde{G}}) \psi_\mu(\mathbf{k}, \lambda) &= 0
\end{aligned}$$

Gravitino Interactions with the MSSM

The relevant supergravity Lagrangian reads

$$\mathcal{L}^{(\alpha)}_{\widetilde{G},\,\mathrm{int}} = -\frac{i}{\sqrt{2}M_{\mathrm{P}}}\left[\mathcal{D}^{(\alpha)}_{\mu}\phi^{*i}\overline{\widetilde{G}}_{\nu}\gamma^{\mu}\gamma^{\nu}\chi^{i}_{L} - \mathcal{D}^{(\alpha)}_{\mu}\phi^{i}\overline{\chi}^{i}_{L}\gamma^{\nu}\gamma^{\mu}\widetilde{G}_{\nu}\right] - \frac{i}{8M_{\mathrm{P}}}\overline{\widetilde{G}}_{\mu}[\gamma^{\rho},\gamma^{\sigma}]\gamma^{\mu}\lambda^{(\alpha)\,a}F^{(\alpha)\,a}_{\rho\sigma}\,,$$

with the covariant derivative given by

$$\mathcal{D}^{(\alpha)}_{\mu}\phi^{i} = \partial_{\mu}\phi^{i} + ig_{\alpha}A^{(\alpha)\,a}_{\mu}T^{(\alpha)}_{a,\,ij}\,\phi^{j}\,,$$

and the field strength tensor $F^{(\alpha)\,a}_{\mu\nu}$ reads

$$F^{(\alpha)\,a}_{\mu\nu} = \partial_{\mu}A^{(\alpha)\,a}_{\nu} - \partial_{\nu}A^{(\alpha)\,a}_{\mu} - g_{\alpha}f^{(\alpha)\,abc}A^{(\alpha)\,b}_{\mu}A^{(\alpha)\,c}_{\nu}\,.$$

The index α corresponds to the three groups $\mathrm{U}(1)_Y$, $\mathrm{SU}(2)_I$, and $\mathrm{SU}(3)_c$ with $a = 1, 3, 8$ and $i = 1, 2, 3$, respectively.

Steps

* Calculate the partial and the total decay widths
* Employ PYTHIA event generator to simulate the EM and HD products of Z, Higgs bosons, quarks and taus
* Incorporate in the BBN code the effects of the EM and HD injections
* Estimate for each point of the SUSY parameter space the light element abundances
* Important point: Bound state phenomena of charged metastable particles like stau!

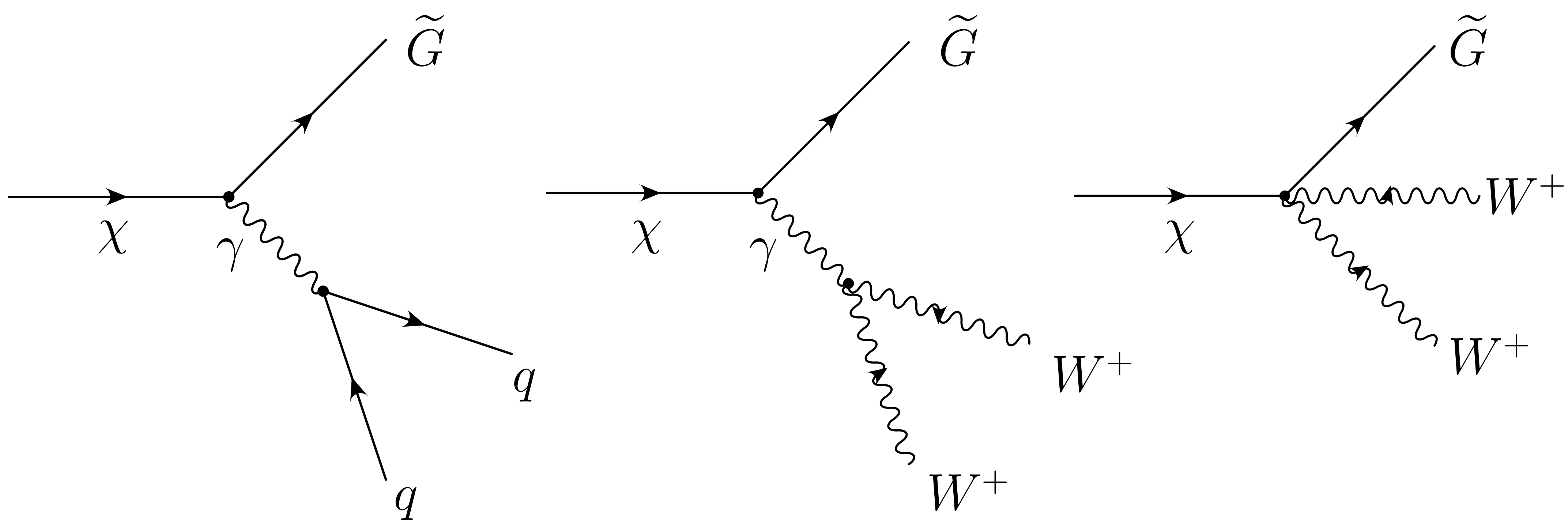
NSP decays

$\boxed{\chi \text{ NSP}}$

$$\chi \to \widetilde{G}\,\gamma$$

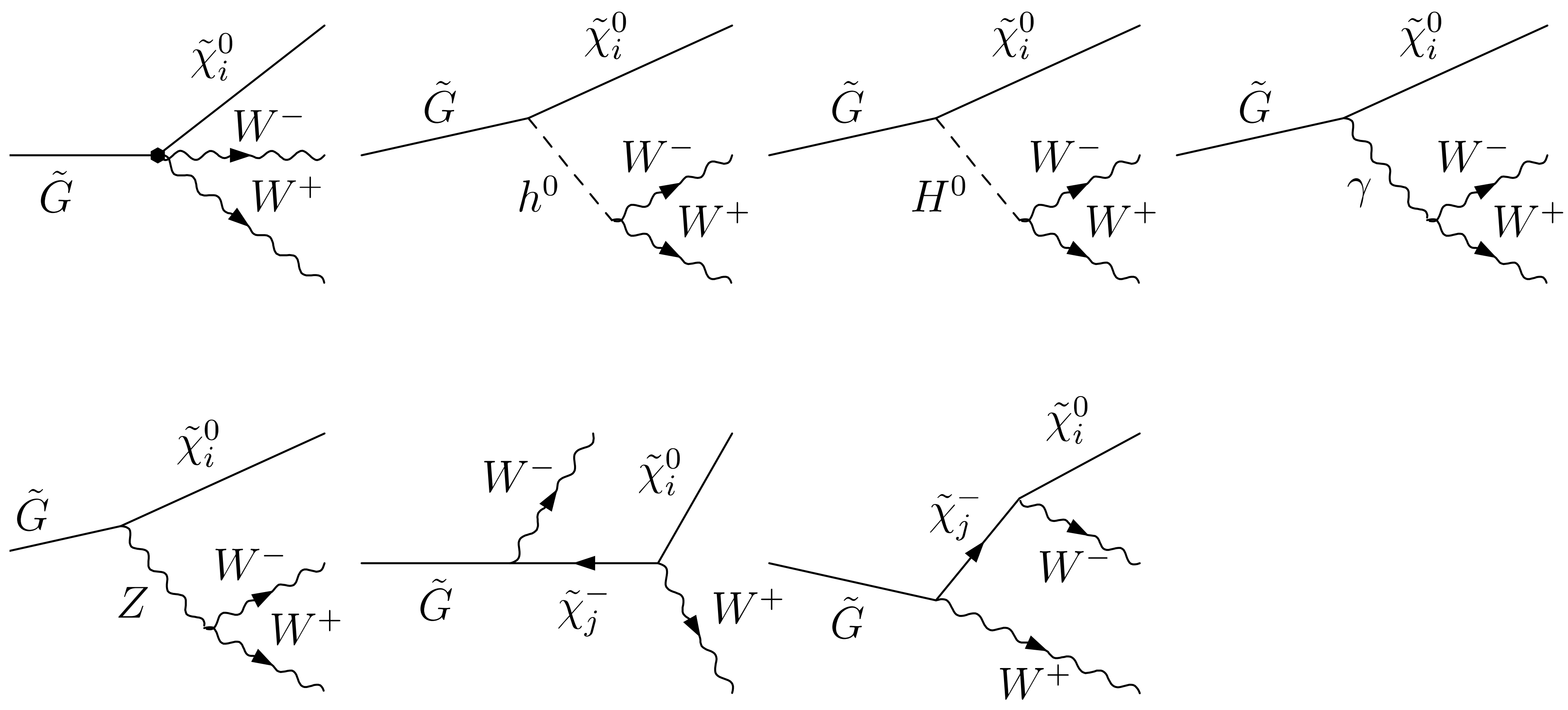
$$\chi \to \widetilde{G}\,Z$$

$$\chi \to \widetilde{G}\,H_i$$



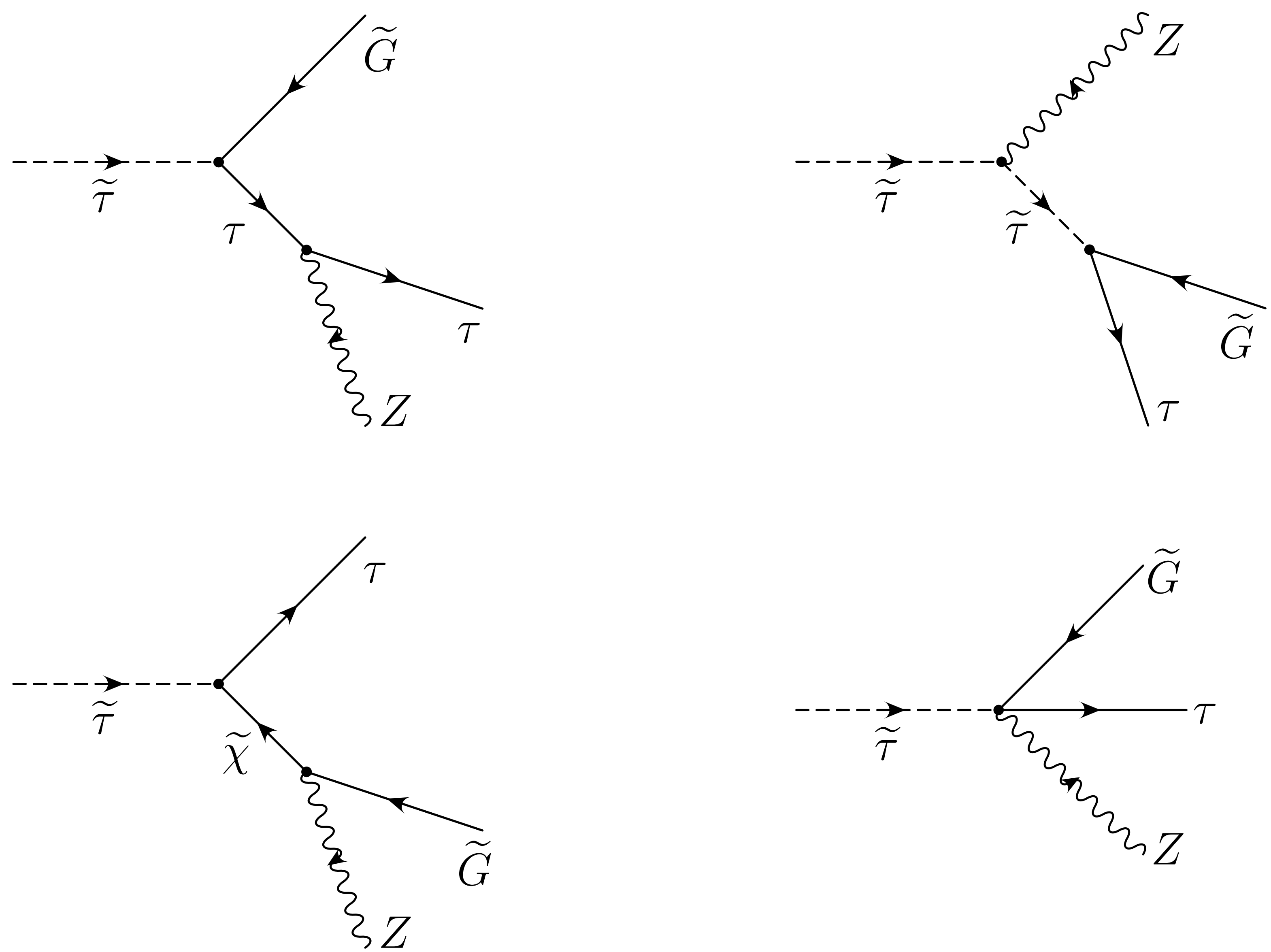
GDM/ GravitinoPack

$$\widetilde{G} \to \tilde{\chi}_i^0 W^- W^+$$



$\tilde{\tau}$ NSP

$$\tilde{\tau} \longrightarrow \widetilde{G}\,\tau$$



GDM/ GravitinoPack

All possible three-body decays of neutralino1 into gravitino

process $\tilde{\chi}_1^0 \to \tilde{G}XY$	number of graphs	first decay $\tilde{\chi}_1^0 \to \tilde{X}Y$	possible resonances
$\tilde{G}f\bar{f}$	7	$\tilde{G}(h^0, H^0, A^0, \gamma, Z^0), f\tilde{f}_l^*, \tilde{f}_l\bar{f}$	h^0, H^0, A^0, Z^0
$\tilde{G}Z^0Z^0$	4	$\tilde{G}(h^0, H^0), Z^0\tilde{\chi}_k^0, \tilde{\chi}_k^0 Z^0$	H^0
$\tilde{G}Z^0\gamma$	1	$\tilde{\chi}_k^0 Z^0$	–
$\tilde{G}W^+W^-$	$6+4pt$	$\tilde{G}(h^0, H^0, \gamma, Z^0), W^+\tilde{\chi}_j^-, \tilde{\chi}_j^+ W^-$	H^0
$\tilde{G}Z^0h^0$	$4+4pt$	$\tilde{G}(A^0, Z^0), Z^0\tilde{\chi}_k^0, \tilde{\chi}_k^0 h^0$	A^0
$\tilde{G}Z^0H^0$	$4+4pt$	$\tilde{G}(A^0, Z^0), Z^0\tilde{\chi}_k^0, \tilde{\chi}_k^0 H^0$	A^0
$\tilde{G}Z^0A^0$	$4+4pt$	$\tilde{G}(h^0, H^0), \tilde{\chi}_k^0 Z^0, A^0\tilde{\chi}_k^0$	H^0
$\tilde{G}\gamma h^0$	1	$\tilde{\chi}_k^0 h^0$	–
$\tilde{G}\gamma H^0$	1	$\tilde{\chi}_k^0 H^0$	–
$\tilde{G}\gamma A^0$	1	$\tilde{\chi}_k^0 A^0$	–
$\tilde{G}W^+H^-$	$5+4pt$	$\tilde{G}(h^0, H^0, A^0), W^+\tilde{\chi}_j^-, \tilde{\chi}_j^+ H^-$	H^0, A^0
$\tilde{G}W^-H^+$	$5+4pt$	$\tilde{G}(h^0, H^0, A^0), W^-\tilde{\chi}_j^+, \tilde{\chi}_j^- H^+$	H^0, A^0
$\tilde{G}h^0h^0$	4	$\tilde{G}(h^0, H^0), h^0\tilde{\chi}_k^0, \tilde{\chi}_k^0 h^0$	H^0
$\tilde{G}H^0H^0$	4	$\tilde{G}(h^0, H^0), H^0\tilde{\chi}_k^0, \tilde{\chi}_k^0 H^0$	–
$\tilde{G}h^0H^0$	4	$\tilde{G}(h^0, H^0), h^0\tilde{\chi}_k^0, \tilde{\chi}_k^0 H^0$	–
$\tilde{G}A^0A^0$	4	$\tilde{G}(h^0, H^0), A^0\tilde{\chi}_k^0, \tilde{\chi}_k^0 A^0$	H^0
$\tilde{G}h^0A^0$	3	$\tilde{G}(A^0, Z^0), h^0\tilde{\chi}_k^0$	–
$\tilde{G}H^0A^0$	3	$\tilde{G}(A^0, Z^0), H^0\tilde{\chi}_k^0$	–
$\tilde{G}H^+H^-$	6	$\tilde{G}(h^0, H^0, \gamma, Z^0), H^+\tilde{\chi}_j^-, \tilde{\chi}_j^+ H^-$	H^0

19 individuel

decay channels

Bound-state catalysis

standard BBN reaction is suppressed

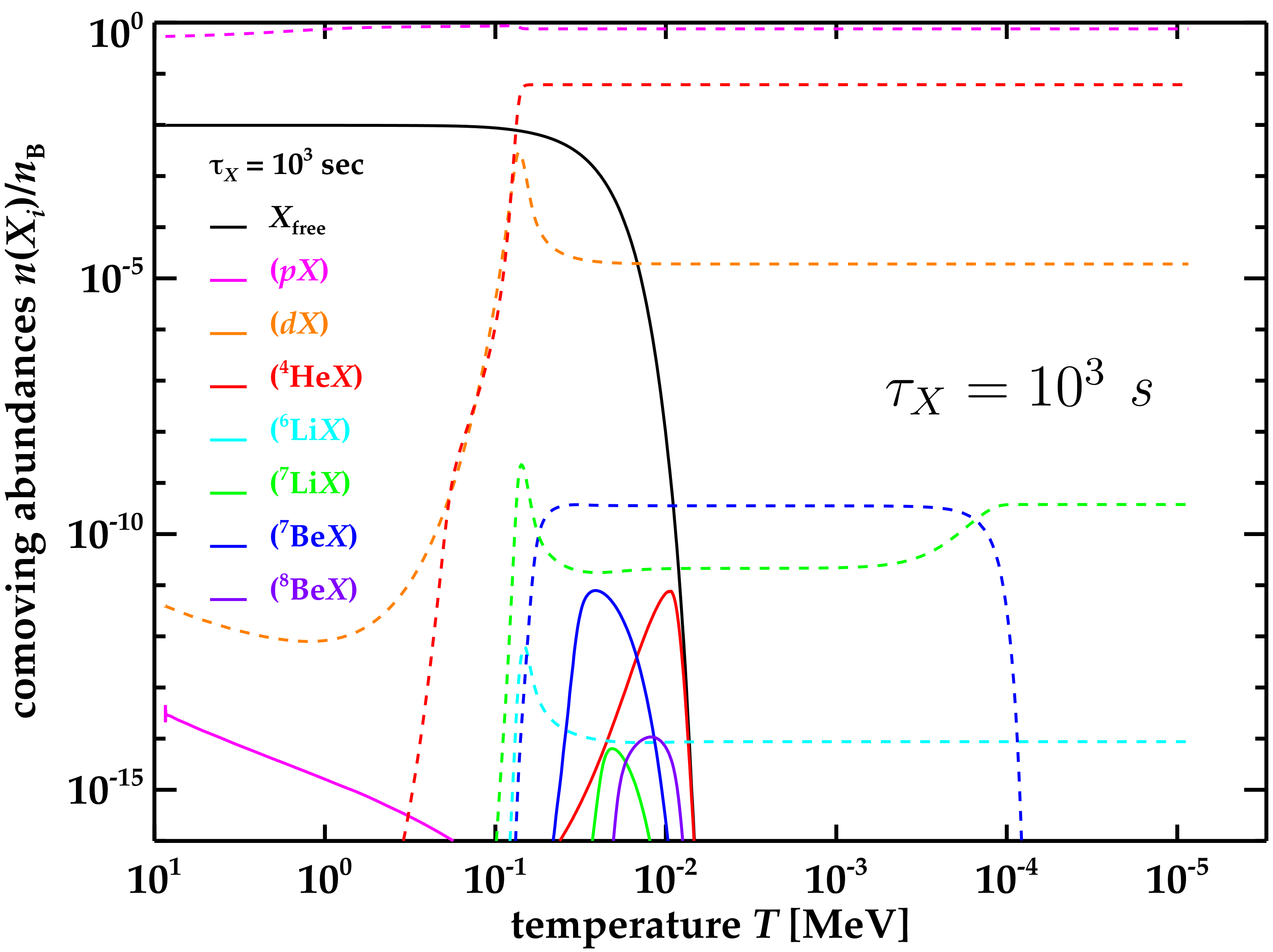
$$^4\mathrm{He} + d \rightarrow {}^6\mathrm{Li} + \gamma$$

the bound state reaction is not suppressed by photon emission

$$(^4\mathrm{He}X^-) + d \rightarrow {}^6\mathrm{Li} + X^-$$

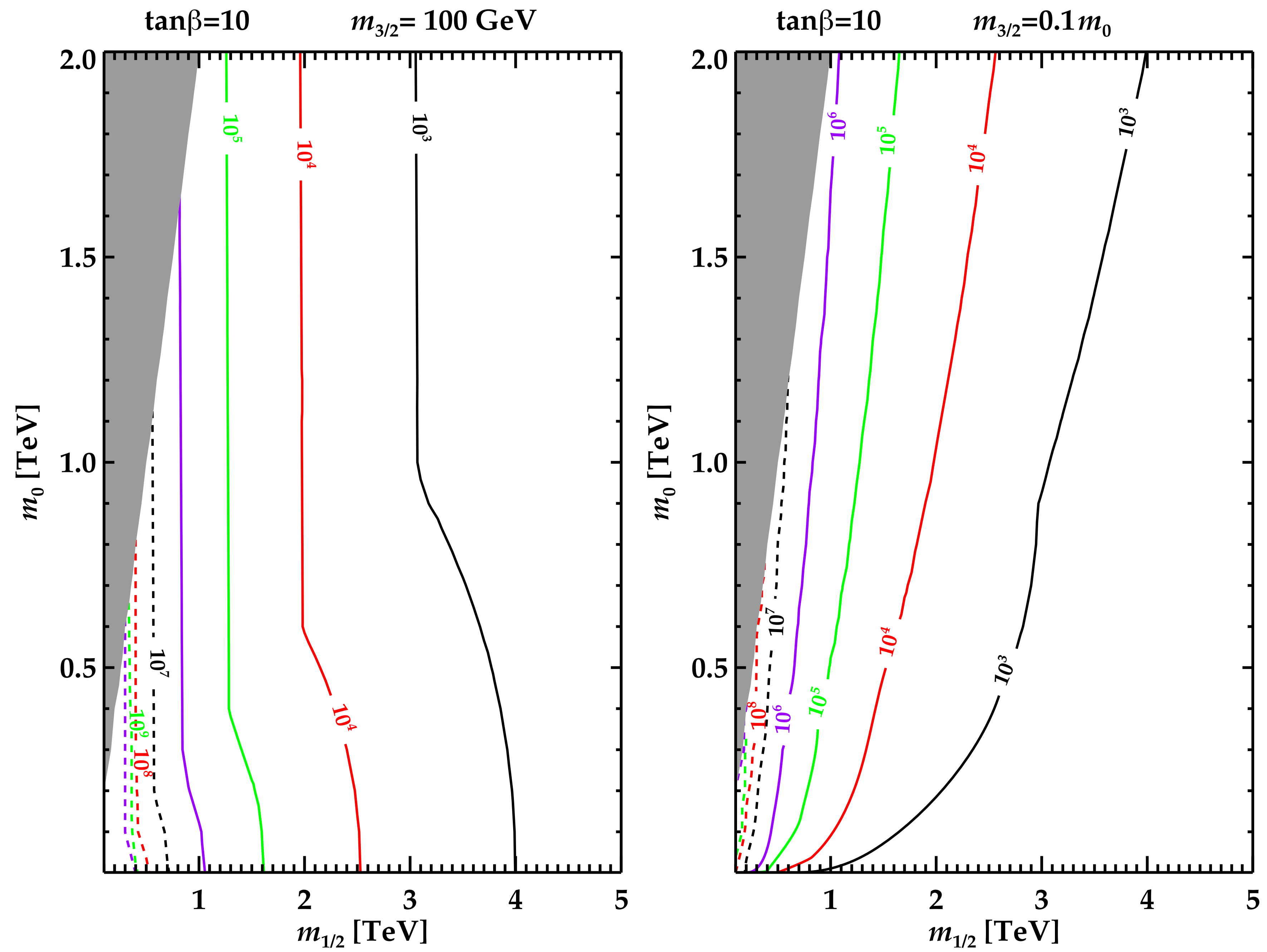
<u>**possible solution of Li puzzle**</u>

M. Prospelov



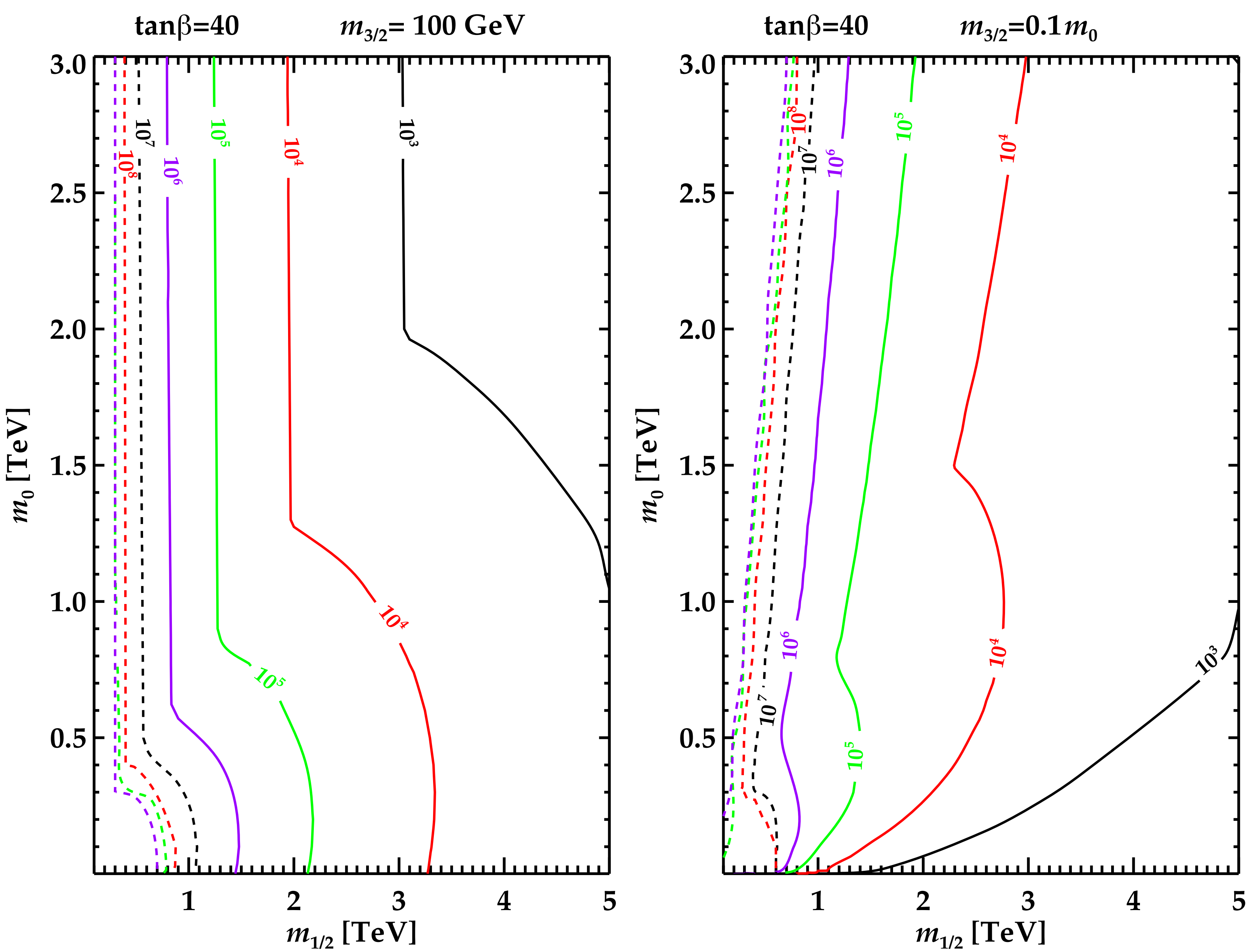
Cyburt, Ellis, Fields, Luo, Olive, VCS, 2012

$$A_0 = 2.5\, m_0$$



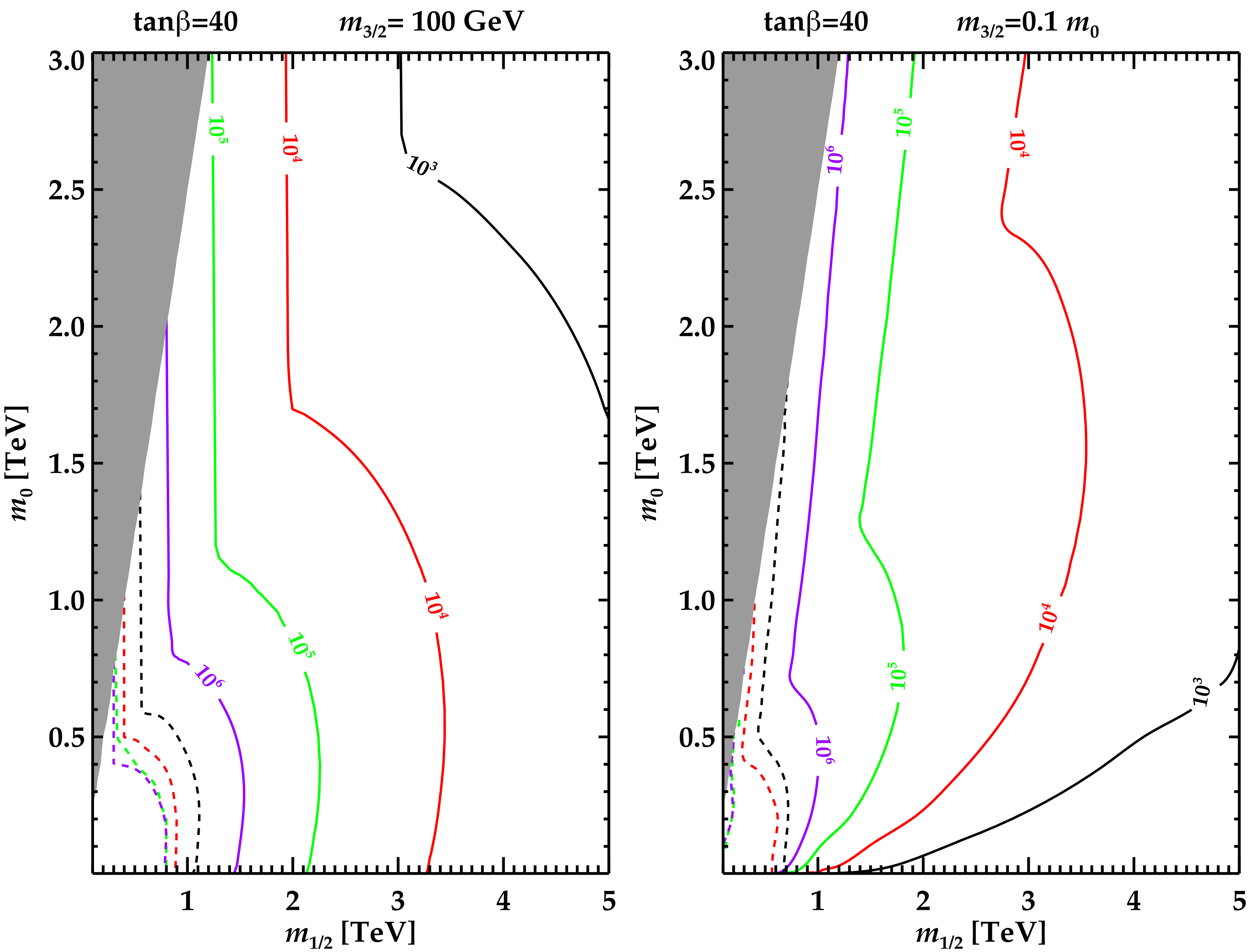
Cyburt, Ellis, Fields, Luo, Olive, VCS

$$A_0 = 2\,m_0$$

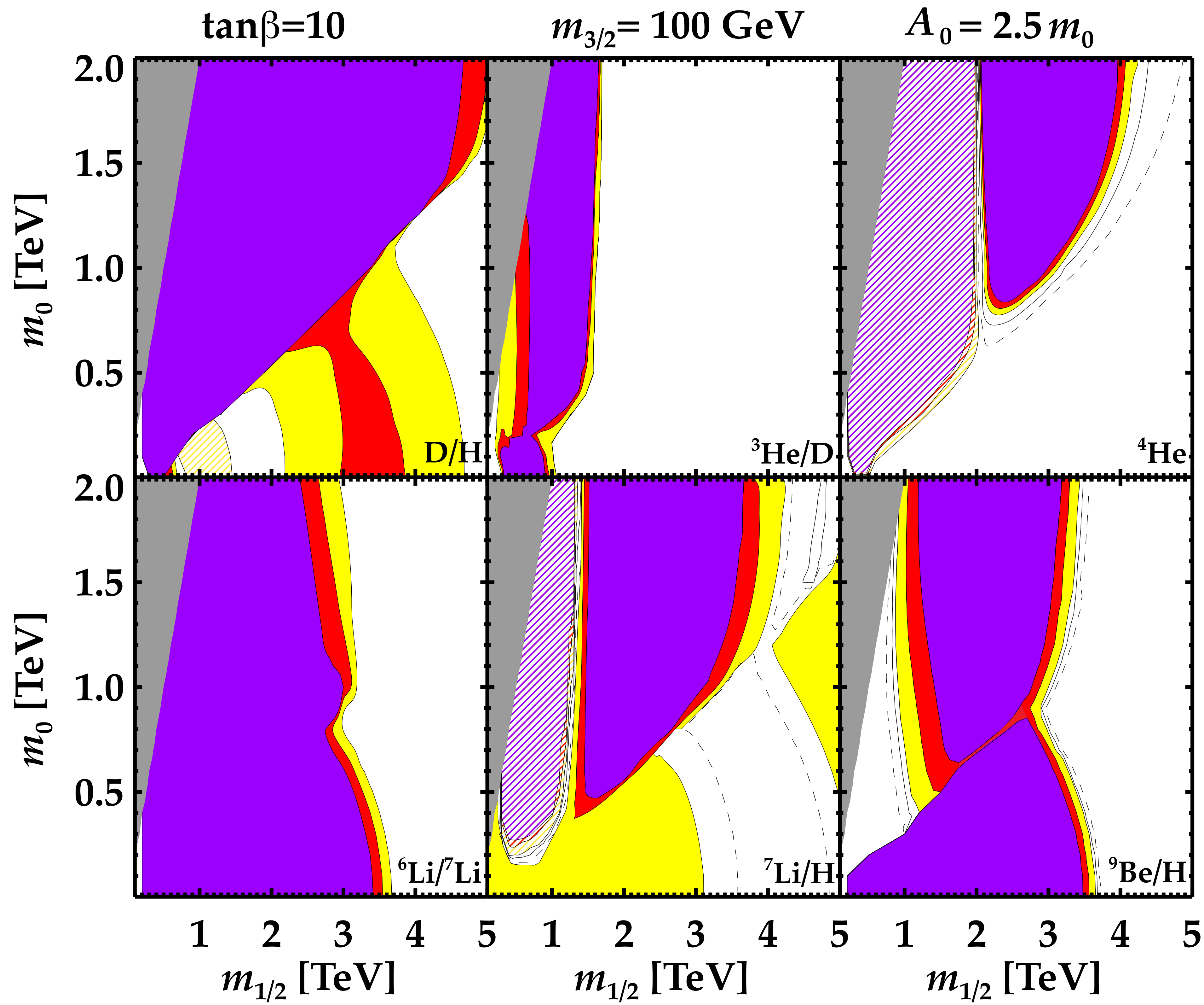


tanβ=40
$m_{3/2}$= 100 GeV
tanβ=40
$m_{3/2}$=0.1m_0
m_0 [TeV]
$m_{1/2}$ [TeV]
10^3
10^4
10^5
10^6
10^7
10^8
0.5
1.0
1.5
2.0
2.5
3.0
1
2
3
4
5

$$A_0 = 2.5\, m_0$$



Cyburt, Ellis, Fields, Luo, Olive, VCS



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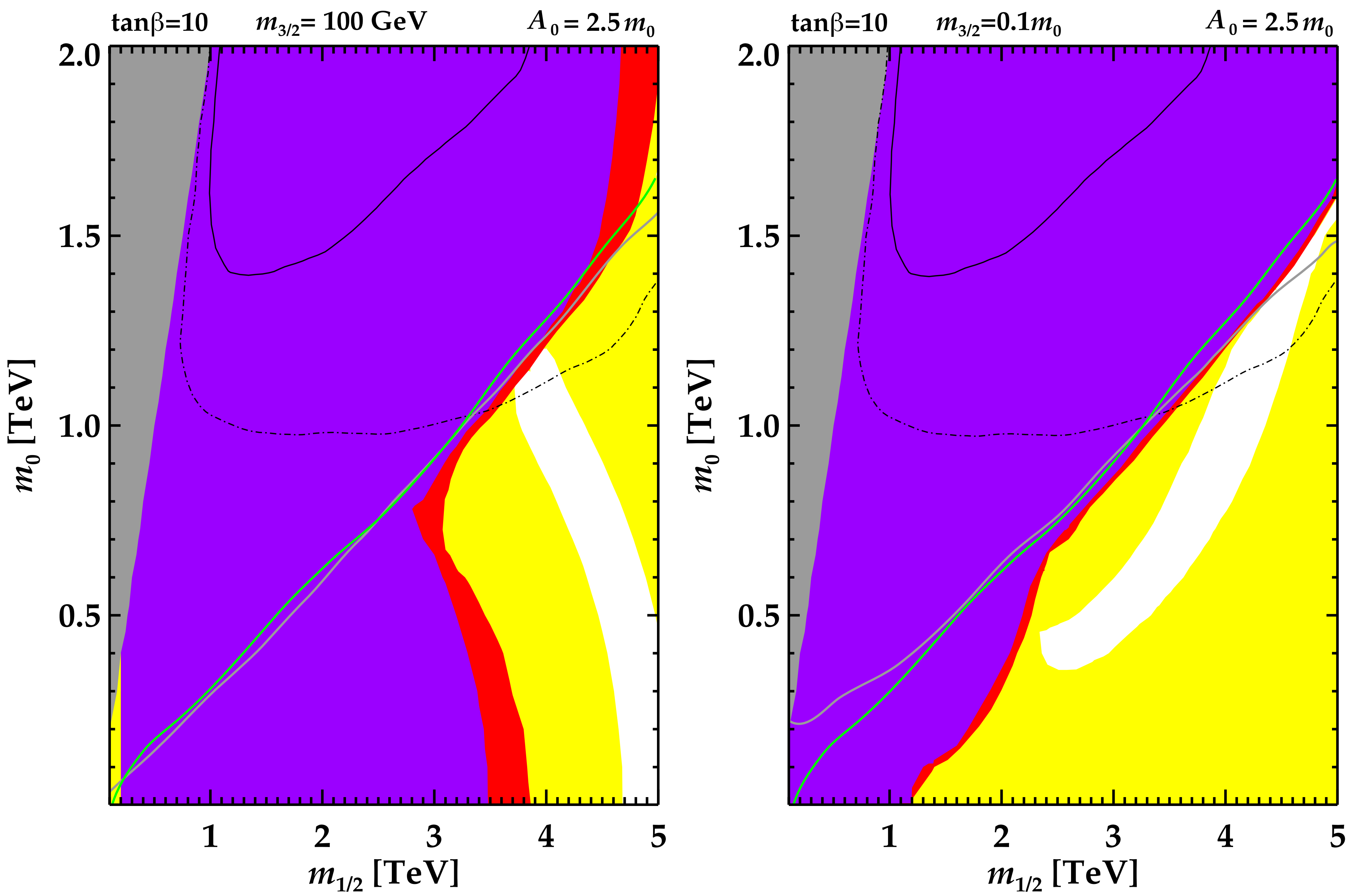
GDM/ results

Gravitino DM parameter space



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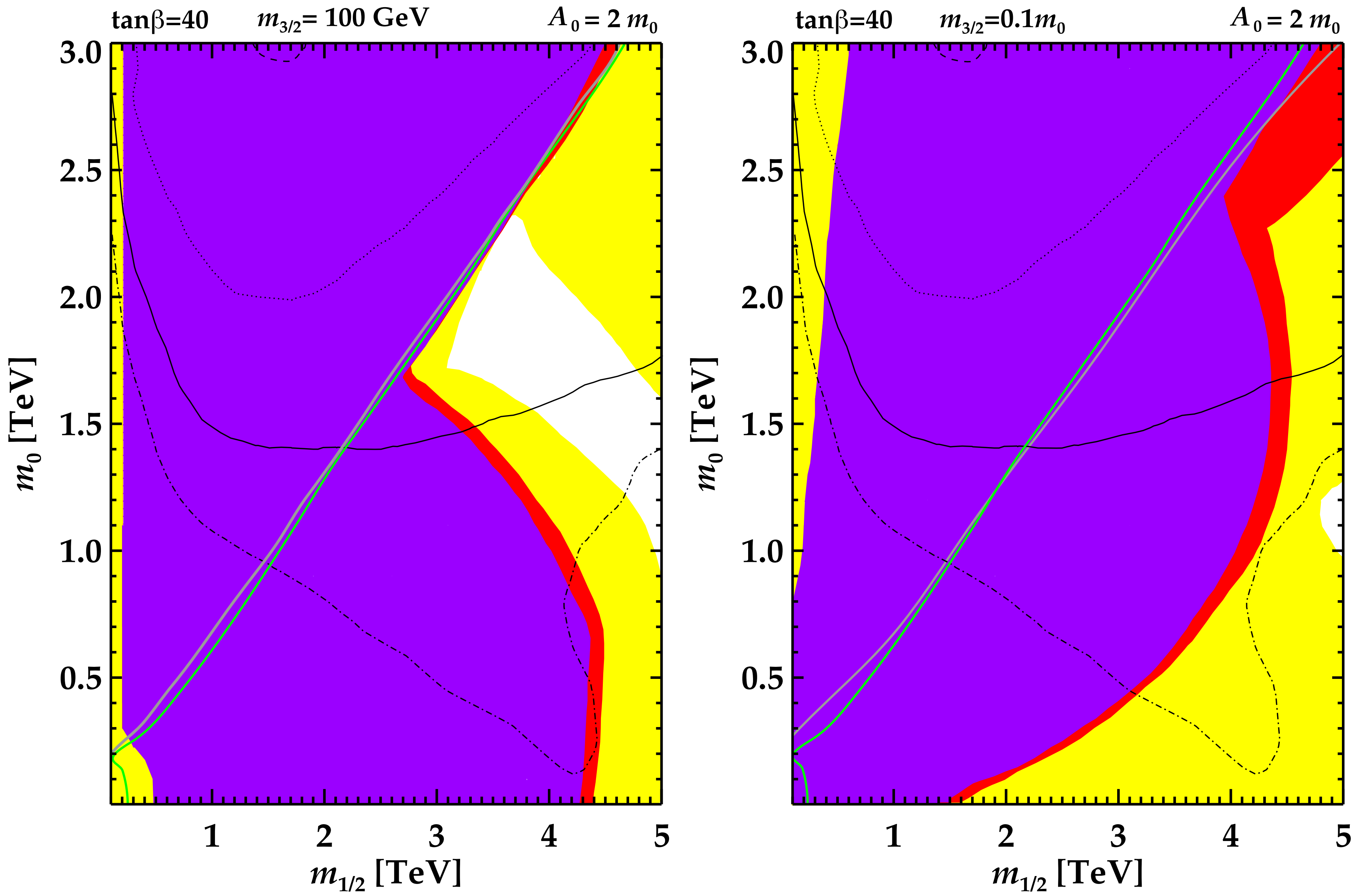
GDM/ results



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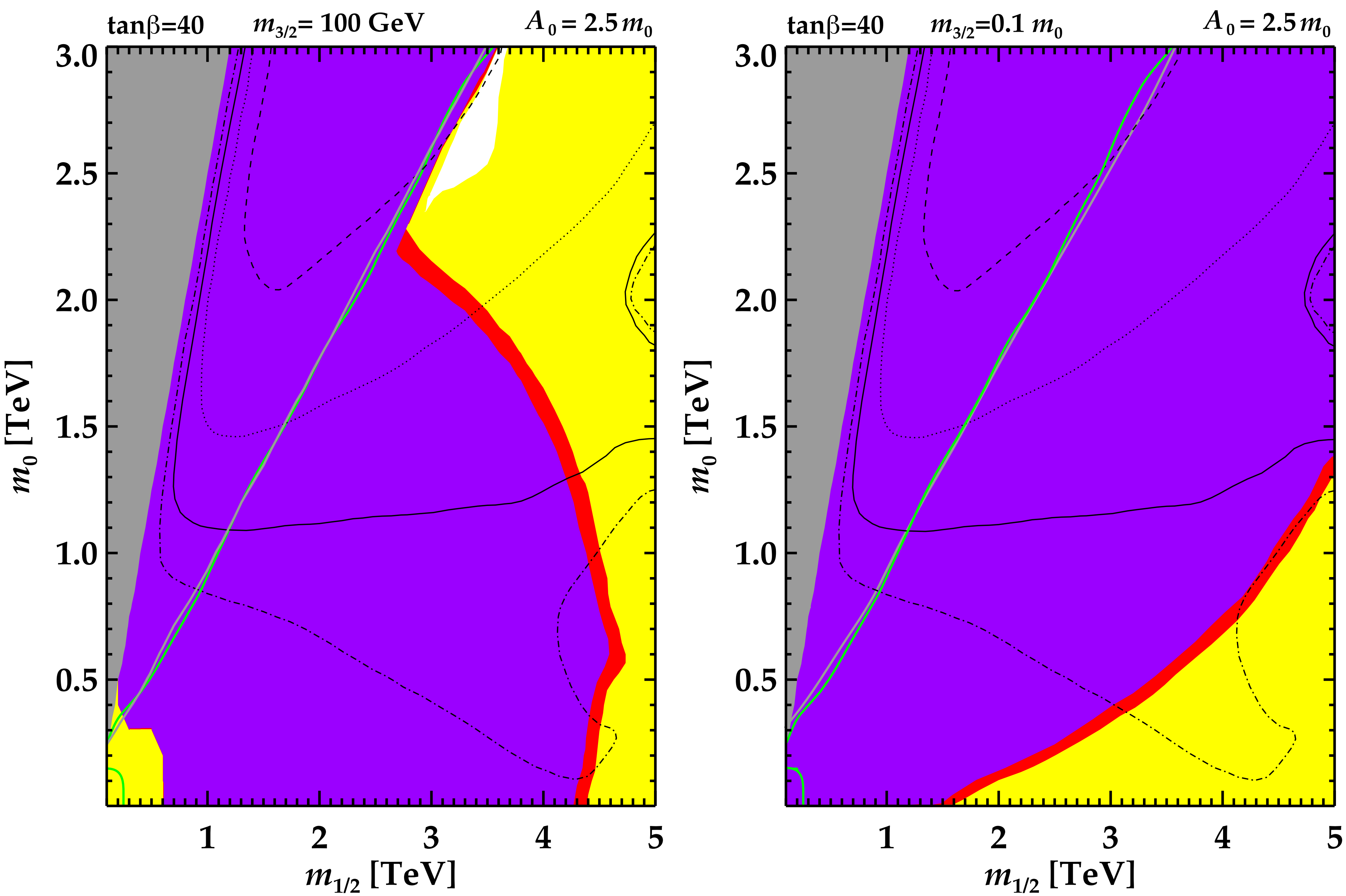
GDM/ results



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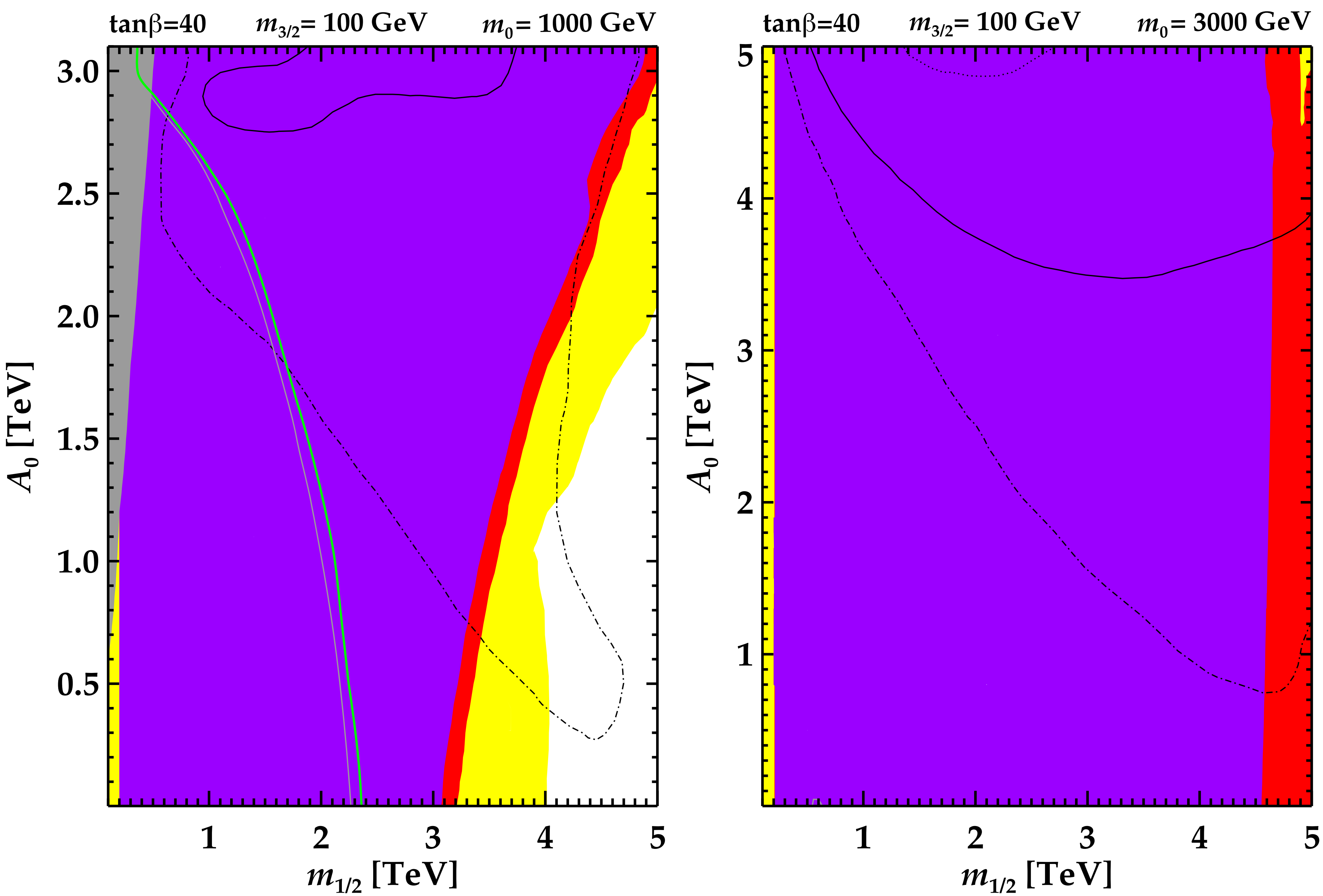

Cyburt, Ellis, Fields, Luo, Olive, VCS

Summary & Prospects

* Gravitino is natural candidate in SUGRA models for DM

* GDM scenario can be quite involved (bound state effects)

* Inclusion of Gravitino thermal production is important to set bound to reheating temperature

* DM scenario and phenomenology can open an window to Planck scale

* **Many-Many Thanks and Congratulations to Keith on his 60th birthday !!**